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MULTISCALE STUDIES OF THE PEATLAND-ATMOSPHERE INTERACTIONS IN NORTHERN EURASIA

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Academic dissertation

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Multiscale studies of the peatland-atmosphere interactions in northern Eurasia

Pavel Konstantinovich Alekseychik

University of Helsinki, 2017

Abstract

North Eurasia (NE) is recognized as a region of high importance for the global climate change. Large and systematic shifts in temperature and precipitation, predicted for NE, are expected to cause irreversible disturbances in the ecosystem-atmosphere interactions. The region is dominated by natural boreal and arctic ecosystems, which are experiencing increasing levels of anthropogenic influence through environmental pollution (mainly agriculture- and mining-related) and land use change. However, despite the general consensus on the importance of environmental changes in NE, many aspects of the problem remain poorly understood. Due to the great extent of NE, many crucial areas remain inaccessible or lack the required infrastructure, thereby relevant surface-atmosphere exchange measurement data remains scarce.

This thesis examines the surface budgets of carbon dioxide and energy of subarctic peatlands, which count among the most important ecosystems in NE owing to their large carbon storage and areal coverage, and their high sensitivity to climate and land use changes. Peatlands are also heterogeneous ecosystems, with large diversity found both internally and between the ecosystem subtypes. Peatland heterogeneity is notable on several characteristic scales, including the single plant, microsite, microtopography element and ecosystem type. Different scales of variation are covered with specific measurement techniques, i.e. plant-scale gas exchange, chamber and eddy-covariance (EC) technique. The latter is in the focus of this work.

Aerodynamic roughness length (z_0) and photosynthesis rate measured by EC were compared with the plant- and microsite-scale measurements of leaf area index (LAI) and photosynthesis rate. High correspondence between the estimates on different scales was found, indicating that the transition between the upscaled plant and ecosystem-scale estimates is possible, and thus adding credibility to both. In the fen Siikaneva-1, LAI showed a strong linear relationship with z_0, while the EC-derived photosynthesis rate closely followed the upscaled plant chamber estimate.

Ecosystem-scale EC measurements made in 2015 at a typical raised bog in West Siberian middle taiga (Mukhrino Field Station) revealed a high cumulative May-August net ecosystem exchange (NEE) of 202 gC m^{-2} and a mean Bowen ratio (ratio of sensible to latent heat flux) of 0.28, which was lower than expected. The surface CO_2 uptake was accelerated by an early spring, and later responded strongly to several major cold fronts; the same reasons apparently led to a low Bowen ratio.

Inter-site differences in terms of energy balance were investigated for a selection of eight Fennoscandian peatland sites with different mire types and management histories. The site mean Bowen ratio ranged from 0.28 to 1.35, evapotranspiration (ET) from 1.2 to 2.8 mm/day, and the decoupling parameter (Ω, indicating the relative strength of radiation and surface conductance controls on evapotranspiration) from 0.11 to 0.48. Generally, the energy balance and ecosystem features were found to be tightly linked, corroborating the predictability of peatland energy balances across a wide spectrum of ecosystems.

Finally, on a yet larger scale, the current measurement station network of the entire NE is discussed. Measurement gaps are identified based on ecosystem type and climate representation by the existing field stations, with the focus on peatlands. Tentative developments for the NE measurement network are proposed. It is established that Siberia is a region very sparsely covered by ecosystem and climate change monitoring sites, especially when state of the art techniques are concerned (e.g. EC). This part of the study was a contribution to the Pan- Eurasian Experiment program (PEEX).

Keywords: climate change, peatlands, carbon balance, energy balance, PEEX

Contents

List of publications

This thesis consists of an introductory review and five research articles. In the introductory part, the papers are cited according to their roman numerals. Paper I is reproduced under the license № 4218741378010 granted by John Wiley and Sons. Papers II, III are reprinted under the Creative Commons Attribution 4.0 License. Paper V is reprinted with the permission of the Editorial board.

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1 Introduction

The Earth's climate shows large variations on various temporal scales – anywhere between decades and millions of years, and those changes are distributed very unequally over the globe (IPCC, 2007). Various reasons are to blame, although the role of human activities has been rapidly increasing in importance over the last two centuries. Moreover, different ecosystems have unequal capacities to sustain the climatic changes, with peatlands being a rather vulnerable one (Gorham, 1991).

In this perspective, Northern Eurasia (NE) represents a region where three important challenges combine. First, it is the region where the climatic changes will probably be some of the strongest worldwide. A large temperature change towards warming and a redistribution of precipitation patterns are expected (IPCC, 2007). Second, NE is also home to the world's biggest peatlands, with the total area in Boreal and subarctic Eurasia of about $3 \cdot 10^6$ km^2. Finally, the anthropogenic influence is growing; large peatland areas in certain parts of NE have been drawn into agriculture and forestry uses, while peat extraction for fuel is nearly ubiquitous (Maljanen et al., 2010).

The boreal peatlands owe their climatic importance to their vast organic carbon stocks, which are estimated at 500±100 GtC (Gorham et al., 2012). However, their future under a changing climate is uncertain (e.g. Frolking et al., 2011; Wilson et al., 2016), as northern peatlands only thrive in relatively narrow climatic bounds, requiring an annual precipitation of 500-3000 mm and a mean temperature of 3-6 ˚C (Wieder and Vitt, 2006; Gignac and Vitt, 1994). Reintroduction of just a fraction of the peatland carbon to the atmosphere would have serious consequences for the climate system (IPCC, 2013, 2014). So far, on the millennial time scales and shorter, boreal peatlands have been accumulating carbon (e.g. Yu et al., 2011), but the balance may change with even minor environmental pressure (Erwin, 2009). All this makes a detailed knowledge of the peatland-atmosphere carbon exchange one of the major current research questions.

Shifts in the energy balance, associated with the land-use and climatic changes, constitute another broad focus of peatland studies. Natural peatlands are known to be the areas with the highest latent heat fluxes in the Boreal landscape (Kasurinen et al., 2014) and albedo higher than that of a boreal conifer forest (Lohila et al., 2010; Gao et al., 2014), thus exerting a cooling effect on the atmosphere. This feature makes the peatlands valuable regional stabilizers of the boreal climate. Peatland management through alteration of vegetation cover, drainage and pet harvesting seems to substantially affect the site hydrology (e.g. Price, 1996; Price, 1997), a characteristic crucial for the energy balance.

NE, including its boreal and Arctic parts, remains one of the largest "white spots" of environmental research, with Russia east of the Urals representing their greater fraction. It offers an expanse of regions that are hard to access, with poor infrastructure and often challenging weather conditions. These are among the major reasons explaining the sparseness of the network of measurements in the region (Kulmala et al., 2011;

Lappalainen et al., 2016). Furthermore, the wide range of climates multiplied by the number of ecosystems yields a very large number of unique environments, of which only a minority are continuously monitored at the moment. This obviously limits the reliability of climate projections, on all scales up to the global.

Thus, certain features of peatlands, including their ecological diversity and highly site-specific features, necessitate the use of the multi-scale and cross-disciplinary approach. For comprehensive understanding of the peatland CO_2 and energy balance, one should consider several scales of variation: plant, microsite, ecosystem, ecoregion, continent. Correspondingly, **this thesis discusses and seeks connections between processes relevant at different scales, and pursues the following aims:**

- to elucidate the important aspects of vegetation dynamics on a small scale, and build links to ecosystem-scale phenomena, including photosynthetic rate, net ecosystem exchange, leaf area index and roughness length (**Papers I** and **II**);
- to determine and compare the energy budgets of a representative selection of peatland ecosystems characterized by a range of natural and land-use features (**Papers III** and **IV);**
- to establish a setup for surface exchange measurements in a West-Siberian bog in order to extend the observational network and to compare its energy and CO_2 budgets with the estimates from other boreal peatlands (**Paper III**);
- to make an overview of the Eurasian continent-scale environmental monitoring efforts (**Paper V**).

2. Background: peatland-atmosphere exchange processes at different scales

Ecosystems and atmosphere are engaged in several kinds of interaction. In terms of climatic effect, these include, most importantly, the surface-atmosphere exchanges of energy, water and CO_2. This thesis poses questions about different aspects of these interactions and their aspects relevant at different spatial and temporal scales. Therefore, the structure is governed by the hierarchy of processes and measurement approaches. **Papers I-IV** examine the processes on plant, ecosystem, and multiple-ecosystem scales. Fig. 1 schematically demonstrates the spatial scales and the main processes studied on each scale. In this section, we will give an overview of the main classes of interactions, scales and approaches to be discussed below, in accordance with the presentation in Fig. 1. The concepts appearing in Fig. 1 are explained in the corresponding sections.

2.1 Plant-scale leaf area and photosynthesis and their upscaling

In this thesis, two problems linked to small-scale processes appear, namely, plant-scale photosynthesis and leaf area (see Fig. 1). The amount of green biomass and the photosynthesis rate constitute important measurable features of any individual plant and plant species. The larger the leaf area, the higher is the potential photosynthesis of a plant;

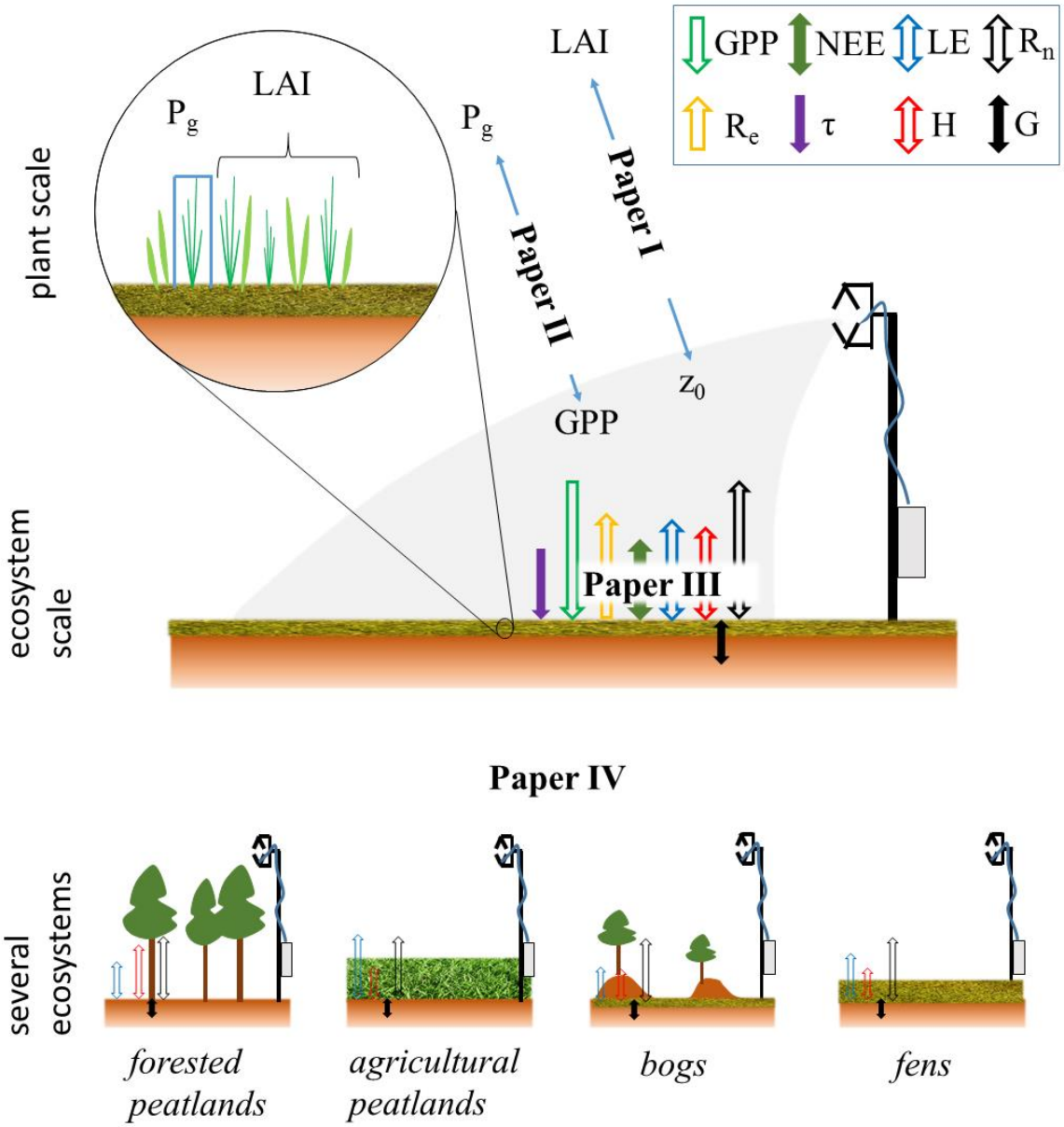

Figure 1. Conceptual presentation of peatland research on different scales discussed in this thesis. The scales are: individual plant scale, ecosystem scale (EC footprint), several peatland ecosystems of different types. P_g is the individual plant-scale photosynthetic rate, GPP the gross primary productivity, LE the latent heat flux, R_n the net radiation flux, R_e the total ecosystem respiration, τ the momentum flux, H the sensible heat flux and G the surface ground heat flux.

therefore, both concepts are closely related. Leaf area is a widely used concept expressing the aboveground plant biomass abundance, defined as the area of green plant parts (stem and/or leaves) per ground area [m^2 m^{-2}]. Leaf area of peatland vegetation can be measured in the lab by an optical device such as LiCor LI-3000, or estimated as length of stem or

needles. Similarly, for an individual of any species, gross photosynthesis (P_g) can be determined, also in the lab. It is known that leaf area and P_g vary substantially among the boreal peatland plant species (e.g. Small, 1972; Korrensalo et al., 2016). The species differ not only in the seasonal amplitude of leaf areas and photosynthesis and in the timing of their maxima. Having the exact species-wise data is important, although, despite a relatively low plant species diversity (19 major species in Siikaneva, e.g. Korrensalo et al., 2016; **Paper II**), obtaining it is a very labor-demanding task.

When the species-wise data has been gathered, they can be upscaled to the ecosystem level, if the species cover fractions are known for an area representative of the entire ecosystem. In the case of **Paper II**, this was done in 121 plots within a circle of 30 m radius around the EC tower.

Upscaling the leaf area yields leaf area index (LAI), which therefore can be interpreted as an area- and species-cover weighted average leaf area of the ecosystem. Applied to P_g, the upscaling procedure results in an estimate of ecosystem-scale photosynthesis, the analogue of GPP obtained from EC measurements. As the laboratory measurements of P_g and P_n yielded estimates per leaf area, they could be transferred to the EC footprint using the linear relationships between species cover and LAI; this survey covered a 200 m radius circle around the EC tower.

2.2 Ecosystem-scale exchange of CO_2

Taking a big step from plant to ecosystem, we may now define a new set of concepts relevant for this scale. The surface CO_2 balance may be represented as net ecosystem exchange (NEE), a sum of two components, the gross primary productivity and total ecosystem respiration:

$$NEE = R_e - GPP. \quad (1)$$

NEE may be of either sign, depending on which component dominates, so that a negative NEE indicates net uptake, and positive – net release of CO_2, by convention. The diurnal dynamics of NEE is complicated by the fact that at night, it is comprised of only R_e, whereas at day, the GPP is added, representing photosynthesis.

Understanding the exchange of CO_2 over the entire ecosystem (an assemblage of vegetation species, terrain, soil types, etc.) is central to this thesis. Owing to the climatic conditions under which they formed, the boreal peatlands possess certain characteristics placing them apart from other boreal ecosystems. Steady long-term accumulation of carbon is one feature that unquestionably lends importance to peatland CO_2 balance. Mass-wise, CO_2 fluxes constitute a major component of the overall boreal peatland carbon cycle (Limpens et al., 2008).

Boreal peatland ecosystems show a fragile carbon balance with an NEE that oscillates widely depending on weather before and during the growing season (Peichl et al., 2014; Helfter et al., 2015). The reported annual NEE values range from about -100 to 100 gC m^{-}

^{2}, while the typical values are constrained more conservatively between [-20, 60] gC m^{-2} (Limpens et al., 2008). Lafleur et al. (2003) report a very wide annual NEE variation in Mer Bleu: -273 gC m^{-2} in a year with favorable weather, but -34 gC m^{-2} in a year with unfavorable weather. However, on the long-term, uptake has been clearly outweighing release of CO_2, which is evidenced by the thick peat layers accumulated across the boreal region. Via a steady accumulation of CO_2, peatlands have, over millennia, become net coolers of the atmosphere, after the effect of CO_2 removal from the atmosphere outweighed the concomitant methane emission (Walter Anthony et al., 2014).

2.3 Ecosystem-scale energy budget

The combination of ecosystem-scale measurements with auxiliary observations also gives an opportunity to gain insight into the energy exchanges of an ecosystem. The key question of the surface energy budget (SEB) is how the energy solar radiation is fractionated into sensible and latent heat fluxes, and storage. The overall energy balance at the surface can thus be written as

$$R_n = H + LE + G + S, \quad (2)$$

where R_n is the net radiation, H the sensible heat flux, LE the latent heat flux, G the soil heat flux, and S the total heat storage in biomass, soil and air (all in Wm^{-2}). However, if it is necessary to compare the turbulent fluxes with the rest of the budget terms (i.e. in order to assess the performance of the EC system), one may rearrange the terms as

$$H + LE = R_n - G - S. \quad (3)$$

Natural peatlands have a distinctive energy balance, characterized by high albedo (e.g. Lohila et al., 2010) and domination of latent heat over sensible heat flux (e.g. Kellner, 2001; Shimoyama et al., 2003; Runkle et al., 2014). The virtually continuous cover of humidified moss, supported by sedges, ensures a relatively unrestrained evaporation (compare the summaries of boreal forest and peatland evapotranspiration by e.g. Launiainen et al., 2016 and Runkle et al., 2014). Previous studies indicated the departure of energy balance in managed peatlands from that typical of a natural open peatland, but such indications remain scarce (e.g. Price, 1996). Section 3.5 continues the discussion of the energy balance components and characteristics.

2.4 Bridging plant- and ecosystem-scale concepts

As reviewed in Sections 2.1-2.3, this thesis utilizes the datasets of quantities measured at different spatial scales. One readily notices two pairs of quantities: species-specific LAI and z_0, P_g and GPP (see Fig. 1). z_0 and EC-derived gross primary productivity represent the ecosystem-scale estimates, while the species-specific LAI and P_g represent the small-scale products which can be scaled up to the ecosystem level. Naturally, the estimates on both scales are expected to be converge, as they target essentially the same quantities, with different approaches. The **Papers I, II** aim to verify this.

The understudied LAI relationship with a micrometeorological parameter, z_0, is in the focus of **Paper I**. Ecosystem-scale LAI is intimately related to ecosystem-atmosphere gas exchange, energy balance, wind shear-induced turbulence (e.g. Bolstad et al., 2001; Leuning et al., 2008; Law et al., 2001; Raupach, 1992; Verhoef et al., 1997). On the other hand, the matter and energy exchanges at the surface are mainly conveyed in the form of turbulent fluxes. The latter is generated and strongly modulated by surface roughness, and assessed in this thesis as aerodynamic roughness length for momentum, z_0; thus, z_0 represents the third key quantity originating from ecosystem-scale measurement (alongside with the CO_2 and energy fluxes). I propose that close relationship with the roughness length for momentum should be expected, since the ensemble roughness of individual plants comprises the very surface roughness that modulates turbulence. In open, treeless mires, this relationship would probably come out most sharply on a seasonal time scale, following the pronounced course in vascular plant leaf area. While single attempts to construct such a relation have been made (Luo et al. 2015), no study dedicated to peatlands has been conducted earlier.

Second, a comparison of photosynthesis on plant- *versus* ecosystem-scale (**Paper II**) was made. Peatland photosynthesis, or GPP, has long been estimated on both plant and EC footprint scales (e.g. Small, 1972' Weltzin et al., 2000; Ward et al., 2009; Alm et al., 1997; Flanagan and Syed, 2011; Peichl et al., 2014), but no thorough comparison of the two independent estimates has been attempted to date. As in the previous case, P_g and GPP, too, should be expected to match, as both evaluate CO_2 sink at the same site.

2.5 Multi-site scale

Natural boreal mires vary considerably in their hydrology, vegetation composition and peat properties. These differences may be formalized using the concept of fen-bog dichotomy (Bridgham, 1996), although the mire types represent a continuum rather than strictly divided classes. The various specific features of natural mires determine their, exchanges of CO_2 and energy with the atmosphere, including, notably, hydrology, vegetation composition and soil structure (e.g. Bridgham et al., 1999; Limpens et al., 2008).

It is not only the natural variation that is relevant, however. The management activities and land-use change in peatlands have already affected a large proportion of the Fennoscandian peatland area. In Finland and Sweden, about 10% of the combined peatland area has been allotted for agriculture, with another 40% drained for forestry (Maljanen et al., 2010; Lohila et al., 2007; Lohila et al., 2004; Shurpali et al., 2009). The anthropogenic incursions modify all crucial peatland ecosystem parameters, such as vegetation, hydrology, and soil structure, which bring about equally drastic changes in peatland-atmosphere exchange processes.

Such a diversity of ecosystem types translates directly into the diversity of the surface budgets of matter and energy (e.g. Beringer et al., 2005; Kasurinen et al., 2014; Limpens

et al., 2008; Maljanen et al., 2010). However, the inclusion of peatlands as a land cover class into regional and global climate models has usually been performed in a very basic way, where many aspects of heterogeneity are over-simplified (Frolking et al., 2009). Making the inclusion of peatlands more explicit means collecting comprehensive data from a range of ecosystem types, and comparing their characteristic features and surface budgets.

Energy balance is a major aspect of peatland-atmosphere interactions (Chapin et al., 2002). As with the carbon balance, its alteration in peatlands entails significant climate feedbacks (Bridgham et al., 1999). Being highly site-specific, the energy balance is a function of weather, vegetation and soil properties, which implies high sensitivity to land-use change in peatlands. Although rebalancing between the sensible and latent heat fluxes and change in albedo is expected to be among the important processes occurring upon peatland management, such data have not been summarized to date. This inter-site variability of energy balances is characterized in **Paper IV** based on May-October surface energy budgets of eight European boreal peatlands.

The scarcity of mire eddy-covariance studies in West Siberia, the biggest Russian peatland province, served as motivation to conduct EC measurements of CO_2 and energy budgets at the Mukhrino Field Station in 2015. Mukhrino is one of the most developed environmental research infrastructures in West Siberia designed for the study of the typical raised bogs of NE. **Paper III** analyses the ecosystem-scale data on the CO_2 and energy budgets in this bog. Further widening the scope of study, this thesis also puts the Mukhrino energy balance data in the context of the **Paper V** results.

2.6 Continental scale

The final, and largest, scale under consideration is that of a continent. North Eurasia covers a vast area and houses a substantial variety of climatic zones (e.g. Peel et al., 2007) and ecosystems, including a broad spectrum of peatlands. The ecosystems found across this expanse are facing a multitude of challenges related to climate and land use change, loss of biodiversity and environmental pollution (Lappalainen et al., 2016). However, the spatial density of field observations made in the region is far from the estimated optimum (e.g. Hari et al., 2015). The current ground-based measurement network of NE strives to cover all the representative sites, but is still far from achieving this task due to the obvious limitations in infrastructure, challenging climate and inaccessibility of many areas.

In this respect, it would be of interest to inquire, how well the existing network represents the ecosystems and climates of NE, and, in particular, of Fennoscandia and Russia, and evaluate the contribution of the sites used in this study. The first necessary step to a coordinated and comprehensive North Eurasian measurement network is to understand, what infrastructures and installations are already available and what environments they represent. Another question is: which environments are not yet covered by any permanent measurements? **Paper V** addresses these problems by means of quantitative meta-analysis

of the North-Eurasian environmental monitoring stations. The geographical distribution (Fig. 2), climate and ecosystem coverage and equipment are among the main discussion topics.

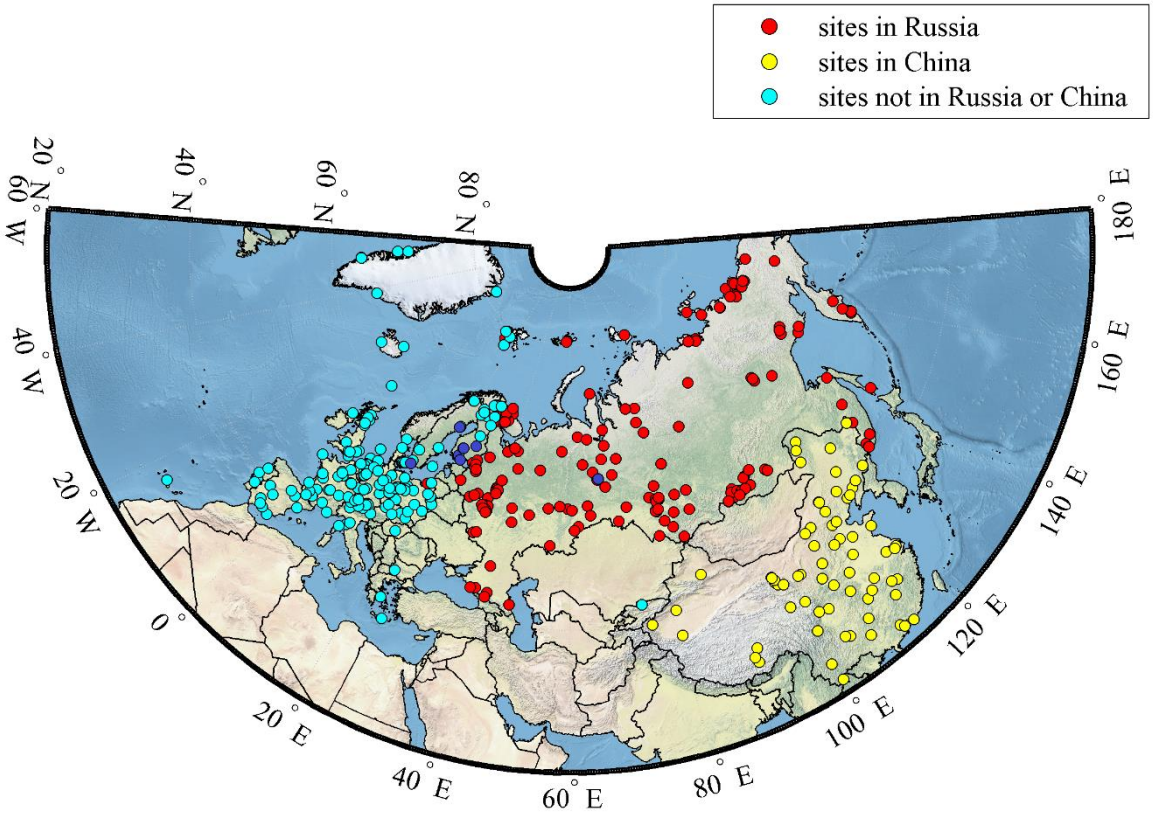

Figure 2. A map of permanent meteorological, ecosystem and measurement sites in Eurasia. The peatland sites whose data used in this thesis (Table 1) are shown in dark blue. Modified Figure 1 from **Paper V**.

3 Materials and Methods

3.1 Measurement sites

A total of nine north Eurasian study sites were selected. The sites are representative of the full range of Boreal peatlands, from natural fens and bogs to those, which have sustained deep anthropogenic impacts. The set includes four ecosystems altered for various uses (two for forestry and two for agriculture), and five ecosystems representing pristine mires (two fens and three bogs). However, diversity is high even within those groups, as each ecosystem possesses its own unique features.

Table 1 classifies the sites into 4 ecosystems types, and gives details about location, former and present status and the thesis publications where they appear.

Table 1. Summary of the measurement sites. RCG – reed canary grass.

	Site name	*Code*	*Country*	*Coordinates*	*Ecosystem type*	*Papers*
1	Alkkia	ALK	Finland	62.2˚ N, 22.8˚ E	bog drained for agriculture, later afforested	IV
2	Kalevansuo	KAL	Finland	60.6˚ N 24.3˚ E	dwarf shrub bog drained for forestry	IV
3	Jokioinen	JOK	Finland	60.9˚ N 23.5˚ E	fen drained for agriculture	IV
4	Linnansuo	LIN	Finland	62.5˚ N 30.5˚ E	fen drained for RCG plantation after peat harvesting	IV
5	Degerö	DEG	Sweden	64.2˚ N 19.5˚ E	pristine fen	IV
6	Siikaneva fen	SI1	Finland	61.8˚ N 24.2˚ E	pristine fen	I, IV
7	Siikaneva bog	SI2	Finland	61.8˚ N 24.2˚ E	pristine bog	I, II, IV
8	Fäjemyr	FAJ	Sweden	56.2˚ N 13.5˚ E	pristine tree-covered eccentric bog	IV
9	Mukhrino	MUK	Russia	60.9˚ N 68.7˚ E	pristine tree-covered raised bog	III

treed peatlands agricultural peatlands

pristine fens pristine bogs

3.2 Eddy-Covariance measurements

The eddy covariance technique is a standard tool for the assessment of ecosystem-atmosphere trace gas and energy fluxes since more than 3 decades (Baldocchi, 2013). The advantages of EC include its directness, noninvasiveness and representativeness of the ecosystem-scale exchange rates (Aubinet et al., 2012). However, the disadvantages consist of the uncertainty in footprint, failure in low-turbulence conditions, workload of maintenance and mathematical complexity, high energy demands for closed-path gas analyzers and susceptibility to precipitation for open-path analyzers. The core principle is high-frequency measurements of the vertical component of wind velocity and a scalar quantity and obtaining their covariances, from which the fluxes of sensible heat (H), latent heat (LE) and carbon dioxide F_{CO2} are derived:

$$H = \rho_d C_p \overline{w'T'} \tag{4}$$

$$LE = \rho_d L_v \frac{M_w}{M_a} \overline{w' \chi_{H_2O}'} \tag{5}$$

$$F_{co_2} = \frac{\rho_d}{M_a} \overline{w' \chi_{CO_2}'} \quad (6)$$

where ρ_d is the dry air density, C_p the specific air heat capacity, w' the vertical wind fluctuation, T' the air temperature fluctuation, L_v the evaporation latent heat, M_w the molar mass of water, M_a the molar mass of air, χ_{H2O}' the fluctuation of water vapor mixing ratio, χ_{CO2}' the fluctuation of carbon dioxide mixing ratio.

When the requirements and assumptions of the eddy-covariance method (steady-state, horizontal homogeneity, absence of advection, flatness of the surroundings) are satisfied, the F_{co_2} in Eq. 6 essentially represents the net flux of CO_2 at the ecosystem-atmosphere interface, which is termed the net ecosystem exchange (NEE) (Aubinet et al., 2012).

Raw EC data of SI1, SI2 and MUK was processed with EddyUH (Mammarella et al. 2016). The software calculates fluxes and performs following the standard routines (Vickers and Mahrt, 1997; Mammarella et al., 2009; Webb et al., 1980; Aubinet et al., 2012).

Ultrasonic anemometer is an integral part of any eddy-covariance system, but the wind data it provides can also be used to obtain the aerodynamic roughness length for momentum,

$$z_0 = z \exp\left(\frac{-\kappa U}{u_*} + \psi_m \right) \quad (7)$$

where z is the height above ground, κ the von Kàrman's constant, U the wind speed at height z, u* the friction velocity at height z, and ψ_m the stability correction function (Paulson, 1970; Webb, 1970).

3.3 Partitioning of net ecosystem exchange into ecosystem respiration and photosynthesis

Being a direct method, eddy-covariance allows for a reliable continuous estimation of NEE. However, this becomes a disadvantage when its principal components, respiration and photosynthesis, need to be determined. Since eddy-covariance is only capable of providing an estimate of *net* flux, extra steps are required to obtain its components. An important application of such partitioning techniques is gapfilling.

EC data are prone to frequent gaps that originate from a wide range of sources: power blackouts, wind direction from the sector disturbed by station infrastructure (e.g. the "mast effect"), inadequate fetch, instrument failure, and insufficient turbulent mixing. The filling of gaps can be executed in a number of ways. In the simplest case, R_e and GPP can be estimated from their known responses to soil temperature (T_p) and photosynthetically active radiation (PAR), respectively. The Q_{10}-relationship for R_e (Davidson et al., 2006)

and the rectangular hyperbola model for GPP (Ruimy et al., 1995; Stoy et al., 2006; Frolking et al., 1998) are traditionally used (Eqs. 8, 9 and Fig. 3):

$$R_{mod} = R_{ref} Q_{10}^{\left(\frac{T_p - T_{ref}}{10}\right)} \tag{8}$$

$$GPP_{mod} = \frac{P_{max} PAR}{k + PAR} \tag{9}$$

where R_{ref} is the reference respiration at the reference temperature T_{ref}, Q_{10} gives the proportional change in respiration at a temperature increment of 10˚, P_{max} is the asymptotic limit of GPP (maximum photosynthesis), and k the value of PAR corresponding to $P_{max}/2$.

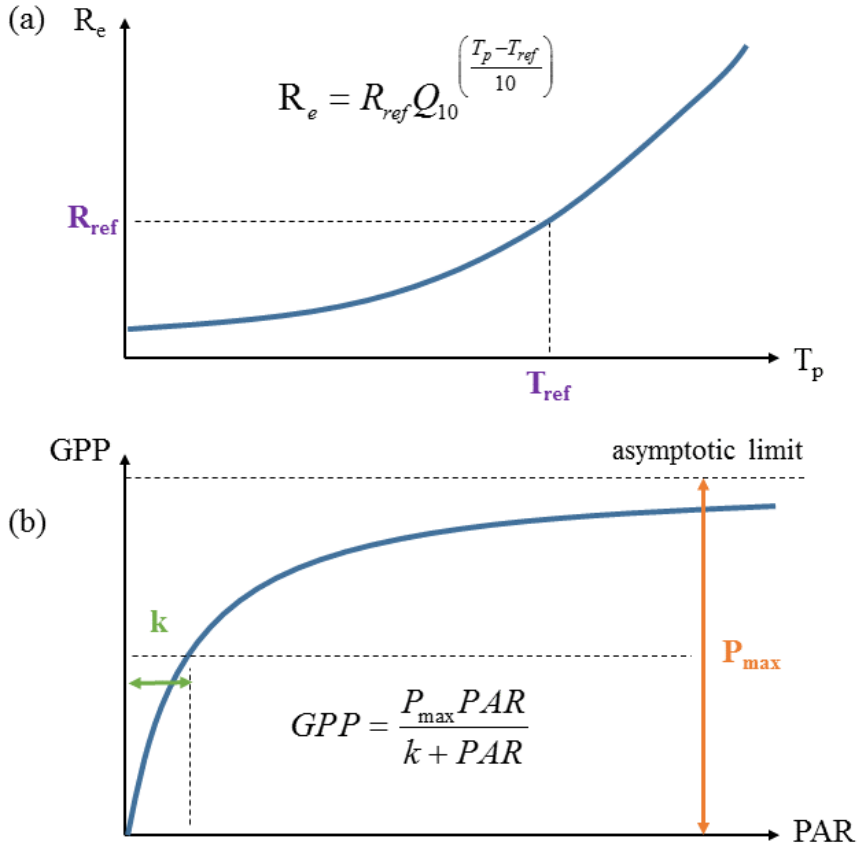

Figure 3. Schematic representation of the temperature (a) and light (b) response functions for R_e and GPP, correspondingly (see Eqs. 8 and 9).

The two minimum necessary steps for NEE partitioning into R_e and GPP are:

1) Use the nocturnal (PAR < 10 μmol m^{-2} s^{-1}) periods to model respiration using Eq. 8. Calculate the R_e model values for night and day.

2) Subtract R_e from NEE to yield GPP; fit Eq. 9 to the GPP *versus* PAR relation, and use the resulting relationship to estimate GPP.

Alternatively, the full NEE equation (NEE = Eq.8 – Eq.9) can be fit to the data for a simultaneous estimation of the respiration and photosynthesis parameters, which was done in **Paper III** to determine the value of Q_{10}.

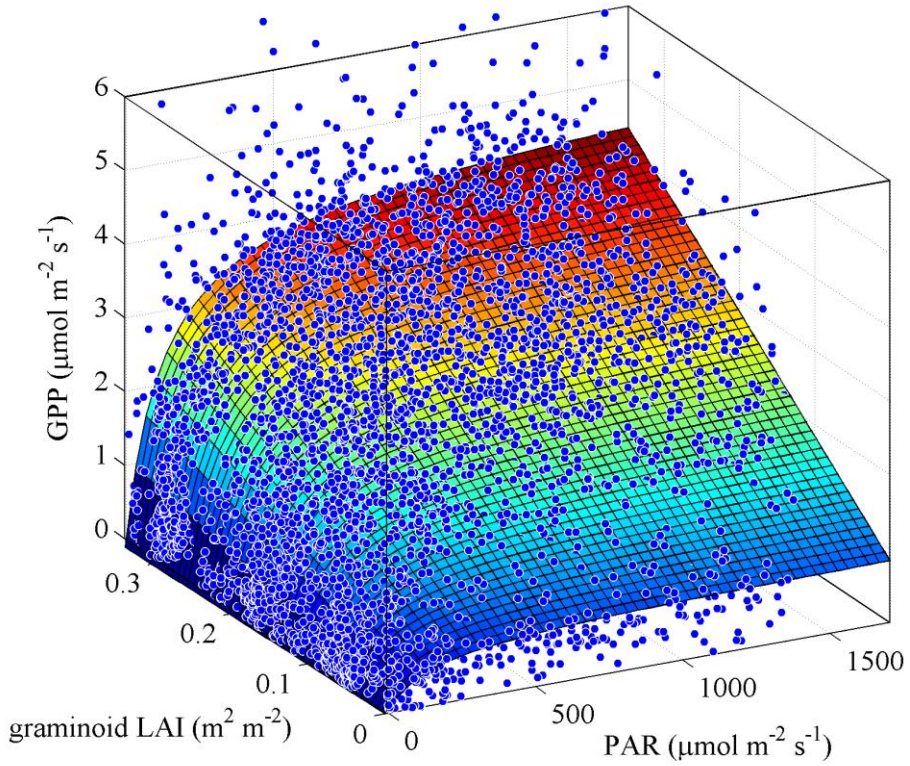

Figure 4. GPP as a function of two variables, leaf area index of graminoids (sedges) and photosynthetically active radiation. A function (Eq. 10) is fit to the SI2 data of 2012-2014. A difference between the GPP levels at LAI extremes can be seen very clearly.

Among all environmental parameters, PAR is the one that largely determines the diurnal course of GPP. However, GPP is not controlled by PAR alone. Leaf area index and temperature become important when the weekly to seasonal time scales are concerned. Since photosynthesis occurs in the green parts of plants, its maximum is roughly proportional to the leaf area index. Therefore, the seasonally changing LAI (graminoids and shrubs) can be added as a multiplier, with a constant summand *a* corresponding to the moss LAI:

$$GPP = \frac{P_{\max} PAR}{k + PAR} \cdot (a + LAI) \tag{10}$$

Fig. 4 demonstrates such a function fit to field data.

Open peatland LAI evolves drastically over the growing season, starting from near-zero level in spring, peaking at about 0.3-0.4 m^2 m^{-2} in summer, and rapidly decaying in autumn (**Paper I**; **Paper II**; Korrensalo et al., 2016). The LAI variation within these wide boundaries causes equally significant changes in maximum photosynthesis (Fig. 4); therefore, LAI must be considered when modeling seasonal GPP dynamics.

When the temperature response is sought, one should consider including the corresponding term in the GPP equation. The air temperature (T_a) response is well described by a Gaussian function including an optimum growth temperature, T_{opt}, and a temperature tolerance, T_{tol} (e.g. Maanavilja et al., 2010):

$$GPP = \frac{P_{\max} PAR}{k + PAR}\left(LAI + b\right)\exp\left(\frac{-0.5\left(T_a - T_{opt}\right)^2}{T_{tol}^2}\right) \quad (11)$$

Eq. 11 includes three important factors controlling photosynthesis, namely, PAR, LAI and T_a. However, even this set of controls is far from complete. While it might seem beneficial to add seasonality, response to air humidity, soil temperature, etc., it is often impractical as such a solution parameters would require long data series. Attempting to model GPP as a function of so many variables may result in overfitting and hence highly uncertain parameter estimates.

A workaround to the above problem consists of going back to Eqs. 8-9 and simply evaluating them for sufficiently short periods. Although the GPP model parameters are now reduced to only P_{max} and k, their variation, if resolved on a short enough timescale, would implicitly describe the time-dependent effects of the entire range of GPP controls. The fitting of Eqs. 8-9 may be performed in a time window about 1-4 weeks long that is shifted by e.g. one day on each iteration, and the resulting series of daily $R_{ref,}$ P_{max} and k values can then be interpolated to the resolution of the EC data (normally 30 min). **Paper III** used this approach with the moving time window length of 4 weeks. The method, which is novel, to our best knowledge, is visually explained in Fig. 5. In principle, if comprehensive seasonality assessment is required for respiration, Q_{10} may be evaluated in the same fashion. However, simultaneous estimation of all four parameters will only be successful when the gaps are few and the window length sufficiently long.

3.4 Microsite-scale measurements and vegetation inventories

A high-resolution vegetation inventory and plant-scale measurements were undertaken in SI1 during the 2005-2007 and 2014-2015 seasons, and in SI2 during the 2012-2015 seasons. The activities, performed mainly by the University of Eastern Finland, yielded ecosystem-scale estimates of the leaf area index, sedge canopy height and species-wise photosynthesis.

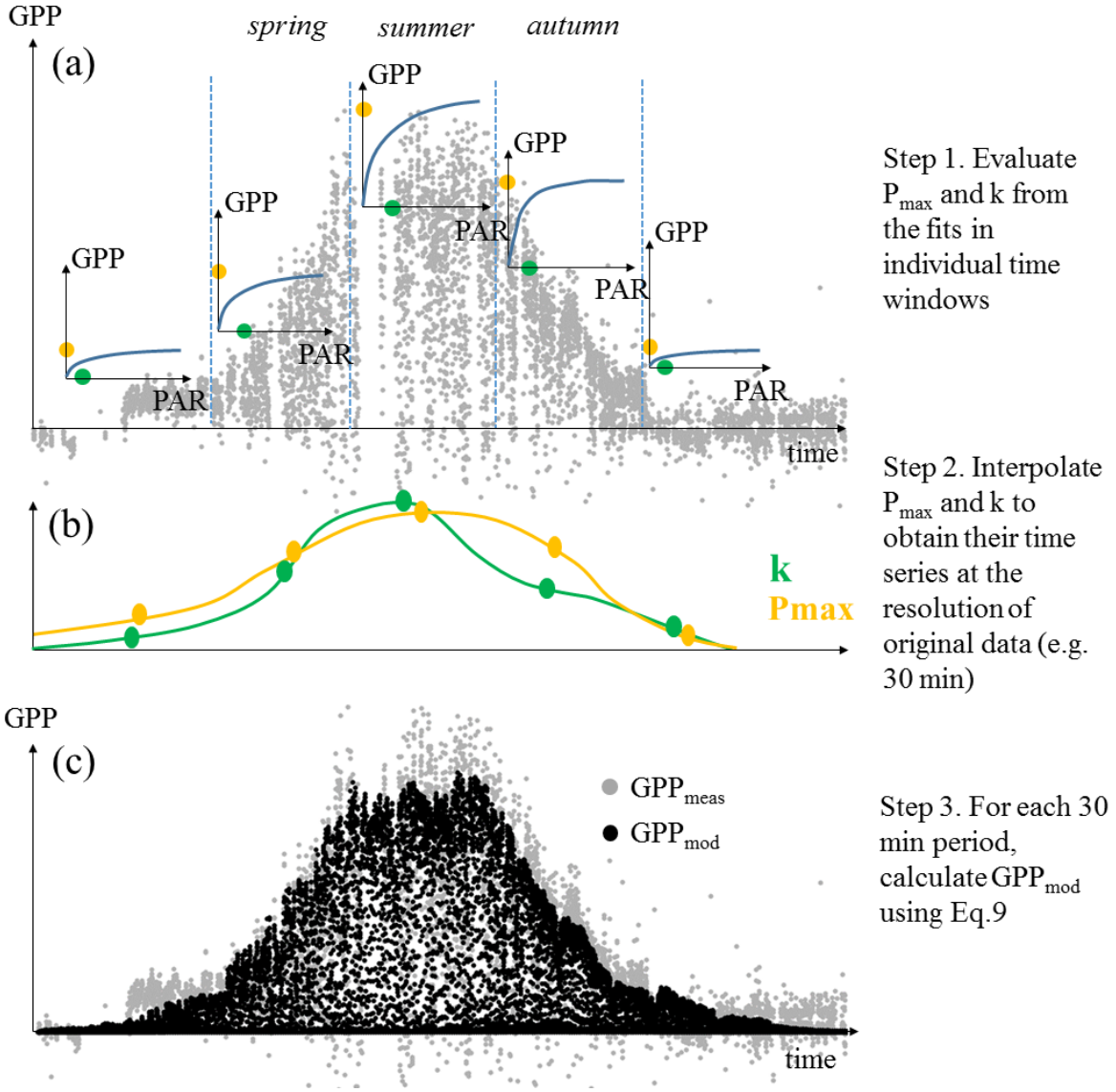

Figure 5. Conceptual representation of GPP modeling via interpolation of the P_{max} and k time series. (a) original GPP, (b) P_{max} and k timeseries, (c) measured and modeled GPP. Cubic spline interpolation was applied on Step 2 (b). The demonstrated GPP data was obtained at the SI1 site in 2014. The k values are shown in green and P_{max} in yellow; see also to Fig. 3b.

LAI

The representative microforms of the SI1 and SI2 sites were covered by 1-7 replicate plots 60 x 60 cm in size, totaling 15 in fen and 18 in bog. Within each, 5 small subplots were defined for the manual measurement of leaf number and length. This measurement was made approximately twice a month throughout the growing season. To obtain the leaf area of the subplots, the leaf number was multiplied by the average leaf area. It should be noted that the method for finding the leaf number changed between the measurement phases in SI1. While originally LAI, was derived for tagged individual plants from their leaf

dimensions, the method was later changed to determining the mean leaf area of a larger sample near the plot with a scanner. These community-specific LAI were then averaged and weighted by their area fractions within EC footprint to yield the ecosystem-scale value. Details can be found in **Paper I**. The leaf lengths of the four tallest sedge species were estimated for the same plots in SI1 following a similar methodology. The average of those was considered to be representative of the ecosystem-scale canopy height.

Plant-scale photosynthesis

Measurements of photosynthesis in 19 main species of the fen site (SI1) were performed in the lab using the Walz GFS-3000 and LiCor LI-6400 devices. The results were used to construct nonlinear mixed-effects models for the species/month combinations (e.g. Mehtätalo et al., 2016; Korrensalo et al., 2016). The modeled species-wise photosynthesis estimates were upscaled to the ecosystem scale using the known relative species cover within a 30 m radius around the EC tower, which corresponds to a major fraction of the EC footprint area. More details about the processing of these data can be found in **Paper II.** The routines are represented schematically in Fig. 6.

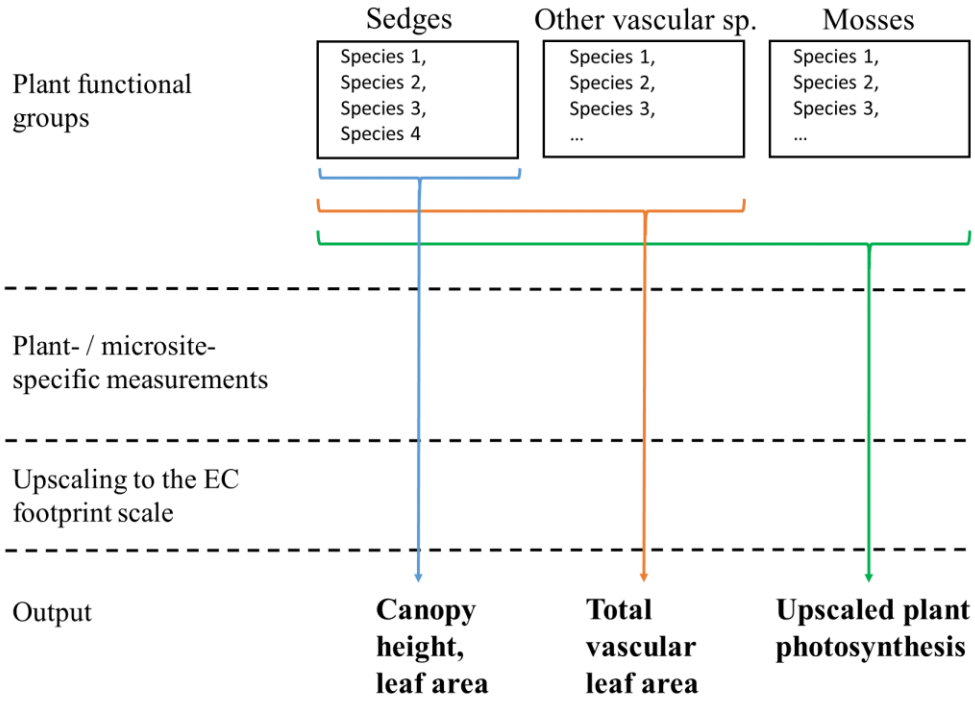

Figure 6. Plant-scale measurements workflow in Siikaneva-1 and 2 sites. The deliverables (canopy height, vascular LAI and upscaled plant photosynthesis) required the use of different sets of plant species.

3.5 From energy exchange to ecophysiology

Even in the absence of direct observations, we are able to approach certain ecophysiological traits of the ecosystem by analysis of energy fluxes and meteorological variables. One such trait is the control over evapotranspiration. The simplest approach was

developed by Bowen (1926), who assessed the fractionation of the available energy (AE = R_n – G) into sensible and latent heat fluxes simply using their ratio

$$ß = H/LE \quad (12)$$

More sophisticated methods were later developed. Penman (1948) represented the evapotranspiration of a water (or just highly moisturized) surface as a function of basic atmospheric parameters:

$$PET_P = \frac{AE \cdot \zeta + (\rho \cdot C_p \cdot VPD \cdot r_a^{-1})}{(\zeta + \gamma) \cdot \Lambda} \quad (13)$$

where ρ is the air density, r_a the aerodynamic resistance, γ the psychrometric constant, ζ the slope of saturation vapor pressure curve, VPD the atmospheric vapor pressure deficit, r_a the aerodynamic resistance, and Λ the latent heat of evaporation. In this case, "well-moisturized" means an easy supply of water to the surface and into the atmosphere, i.e. zero surface resistance. However, in real conditions, the surface is not necessarily moisturized, so that in order to become available for evapotranspiration, the water has to pass through a series of resistances such as stomata, topsoil or moss layer. Consequently, surface resistance r_s should be included, which lowers the estimate of potential evaporation:

$$PET_{PM} = \frac{AE \cdot \zeta + \left(\rho \cdot C_p \cdot VPD \cdot r_a^{-1}\right)}{\left(\zeta + \gamma(1 + r_s / r_a)\right) \cdot \Lambda} \quad (14)$$

This modification was introduced by Monteith (1965). However, in terms of ecophysiology, it is r_s (or conductance, $g_s = r_s^{-1}$ and $g_a = r_a^{-1}$) that raises greatest interest. It is also the only unknown in the equation, as the rest of the quantities derive from routine micrometeorological measurements. Consequently, the Penman-Monteith equation should be inverted in order to yield r_s:

$$r_s = r_a \left(\frac{\zeta \beta}{\gamma} - 1\right) + \left(\frac{\rho C_p VPD}{\gamma AE}\right)(1 + \beta) \quad (15)$$

Here it must be noted that, while g_s is intended to represent stomatal conductance, it in fact represents a combination of parallel conductances of all surfaces found in a given ecosystem, such as leaves, branches, stems, soil, moss, rocks, etc. It is only in the ecosystems with high leaf area index that g_s approaches the stomatal conductance, as there the transpiration from leaves dominates the ecosystem-scale evapotranspiration.

Priestley and Taylor (1972) revisited the Penman equation. In the case of equilibrium evaporation, i.e. such that occurs from a well-watered surface during a passage of a saturated air mass, the aerodynamic term (the second summand in Eq. 13) can be eliminated (e.g. Engström et al., 2002), so that LE is now a function of only available energy and temperature. However, as purely equilibrium conditions are rarely achieved in practice, a dimensionless term, α, compensates for the deviation:

$$\alpha_{PT} = \frac{LE}{LE + H} \cdot \frac{\zeta + \gamma}{\zeta} \quad (16)$$

α is generally regarded as an indicator of surface conditions, such as amount of moisture available for evaporation. In this respect, it is closely related to ß, as recognized already by Priestley and Taylor (1972).

The search for an improved description of the plant physiological regulation led Jarvis and McNaughton (1986) to consider the role of stomatal conductance control. They argued that, on a single leaf scale, there is a continuum between the two extremes: (a) when stomatal closure does not make any impact and (b) when it fully controls transpiration. The situation (a) occurs when e.g. the leaf surface is wet, stomatal aperture is close to maximum, and net radiation at the leaf surface fully controls transpiration; conversely, (b) corresponds to dry conditions when stomatal regulation directly controls transpiration. This principle of varying importance of stomatal (in reality surface) conductance can be expressed with the help of the so-called decoupling parameter Ω:

$$\frac{dET}{ET} = (1 - \Omega)\frac{dg_s}{g_s} \quad (17)$$

where E is evapotranspiration. Eq. 17 essentially states that an increment of stomatal conductance causes an equivalent change in evapotranspiration when Ω = 0; however, at Ω → 1, the effect of stomatal conductance on ET diminishes until it disappears at Ω = 1. Effectively, Ω takes up values from 1 to 0, so that

$$\Omega = \frac{\zeta / \gamma + 1}{\zeta / \gamma + 1 + g_a / g_s} \quad (18)$$

4 Results and discussion

4.1 From plant- to ecosystem-scale

Papers I and **II** aimed to find connections between the plant-scale measurements (leaf area index and photosynthesis) and their ecosystem-scale estimates (eddy-covariance data). The results of these comparisons are discussed in sections 4.1.1-4.1.2.

4.1.1 Relationship between leaf area index and roughness length

The relationship between ecosystem sedge leaf area index (LAI_s) and aerodynamic roughness length for momentum was tested based on measurements in SI1 and SI2. A linear relationship with a high determination coefficient was found (Fig. 7). However, better results were achieved in fen SI1 (R^2 = 0.77-0.80) than in bog SI2 (R^2 = 0.38). The observed R^2 in Siikaneva-1 competes with the best attempts at LAI derivation in other studies, approaching the level of direct field measurement in terms of R^2 and RMSE (e.g.

Sonnentag et al., 2007). Being much less significant, the SI2 relationship is still comparable with some previous LAI modeling attempts having a lower R^2.

Such a level of association between LAI_s and z_0 was, in fact, to be expected. From the standpoint of the wind-ground interaction, the leaf area is, basically, none other than an assemblage of aerodynamic roughness elements. When the surface roughness changes, this inadvertently affects the properties of turbulence in the overpassing airflow, including z_0. Since the LAI_s variation in an open mire has a pronounced annual course (between approximately 0 and 0.5 m^2 m^{-2}), the seasonal change in z_0 is, therefore, easy to register.

The observed z_0 – LAI_s relationship may be used to estimate LAI_s from z_0 (or *vice versa*, if necessary), when only one of the quantities is available. However, the purpose of this study was to propose a method for LAI estimation based on z_0 measurements. As z_0 is quite suitable for continuous monitoring, requiring only basic meteorological measurements, the estimation of LAI_s from z_0 seems feasible for many sites. However, while the linearity of the relationship may be universal, the slope of regression may vary among the sites and needs to be established individually – until a connection between the slope and e.g. canopy structure or microtopography will be established by a future study.

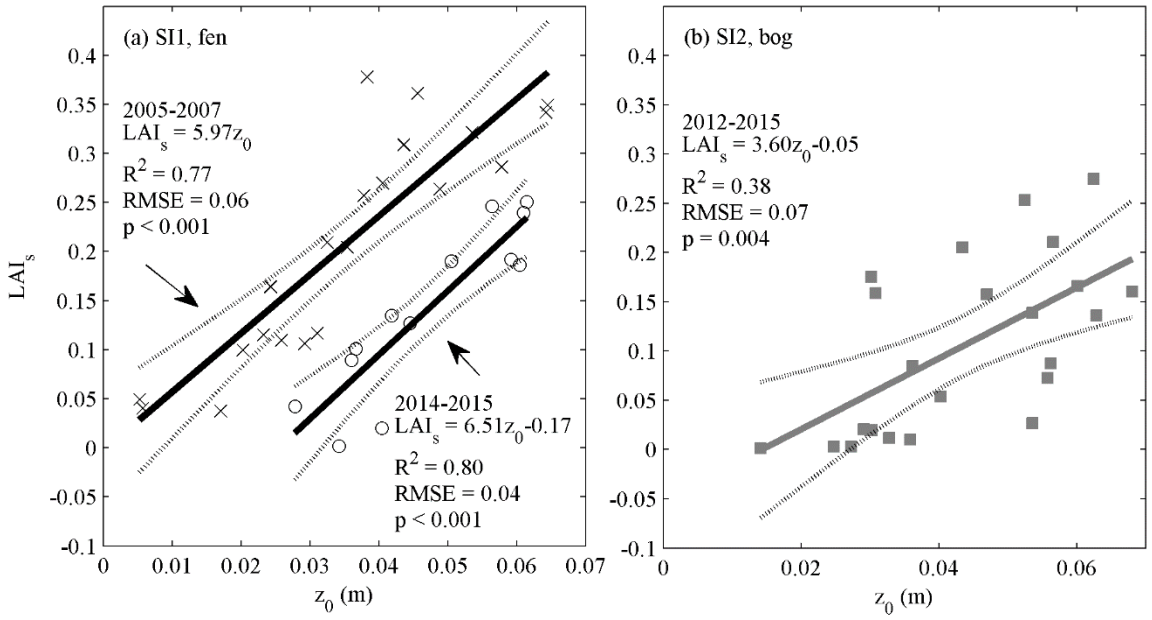

Figure 7. Monthly average values of LAI_s *versus* z_0 in the two study sites, (a) SI1 and (b) SI2. The SI1 data are presented separately for two measurement periods. The linear fits are shown with the functional 95% confidence intervals. Adopted from **Paper I**.

Besides, potential users of this method should be aware of the uncertainties in z0 and LAI measurements. For instance, the difference in the intercept between the two measurement phases in SI1 (Fig. 7a) has, in all likelihood, resulted from the difference in LAI estimation approaches. As discussed in Paper I, the new method used since 2014 seems to be more correct, as extrapolation of LAIs to zero yields z0 = ~0 m in 2005-2007, which is

impossible because sedges are not the only roughness elements present on the mire surface. However, the similarity of slopes of in Fig. 7a is curious.

Finally, a high correlation between vegetation height and z_0 in SI1 fen site has emerged in the study. Because simple relationships ("rules of thumb") still find wide application, we derived a relationship for SI1, $z_0 = 0.27h_s$.

4.1.2 From plant to ecosystem-scale photosynthesis

The laboratory-measured gross plant-scale photosynthesis (P_g), scaled up to the EC footprint, summed up to 230 gC m^{-2} for the growing season (May-September) of 2013. This estimate is based on the 19 main vascular and moss species and is comprised of 138 gC m^{-2} contributed by Sphagnum mosses and 92 gC m^{-2} by vascular plants. On the contrary, in terms of the laboratory-measured net photosynthesis (P_n equaling P_g minus respiration), mosses were a smaller net sink of only 20 gC m^{-2} compared with the vascular plants (57 gC m^{-2}).

The temperature limitation of photosynthesis was relevant throughout the growing season, but especially so in spring. During that period, the moss P_g constituted the dominant fraction of the overall P_g, as the conditions, cool and moist, were more favorable for moss, rather than for vascular plant growth. The difference became largely reduced by June when the ambient temperatures rose. Interspecies ranking in terms of P_g was rather explained by the relative areal cover than by the differences in species-specific photosynthesis (the P_{max} parameter) – i.e., in the whole ecosystem, the most productive species were such simply due to the larger number of individual plants. However, the interspecies differences in respiration again "shuffled the cards", making some low-coverage species important in terms of net photosynthesis, P_n.

Comparison of the EC GPP and the upscaled P_g confirmed the reliability of the latter, as both photosynthesis estimates were generally rather close. The seasonal curves of both independent estimates appear to match (Fig. 8), except in May, when the difference reaches almost 1 gC m^{-2} d^{-1}, or about 30% in relative expression. However, this mismatch proved to be explainable by the difference between laboratory and field temperatures: while the field temperature varied widely, the lab experiments were exposed to a constant 20˚C and the temperature sensitivity was not known. We were able to model this effect of by using an EC GPP model with a temperature module (Eq. 11). The optimum growth temperature obtained from this model fit was 22.6˚C, so that the field measurement of GPP with EC understandably yielded much lower values than the laboratory experiments made in nearly optimum temperature. Fixing the temperature at 20˚C in Eq. 11 eliminated the EC-P_g difference during May and June, pointing at the importance of temperature limitation in these months (Fig. 8). At the same time, the July-August mismatch remained, implying the existence of some other effects, possibly related to water table (WT). The EC photosynthesis estimate may have exceeded the upscaled laboratory estimate because the

field water supply was more optimal for growth, i.e. the surface peat was possibly better moisturized in the field than that in the lab.

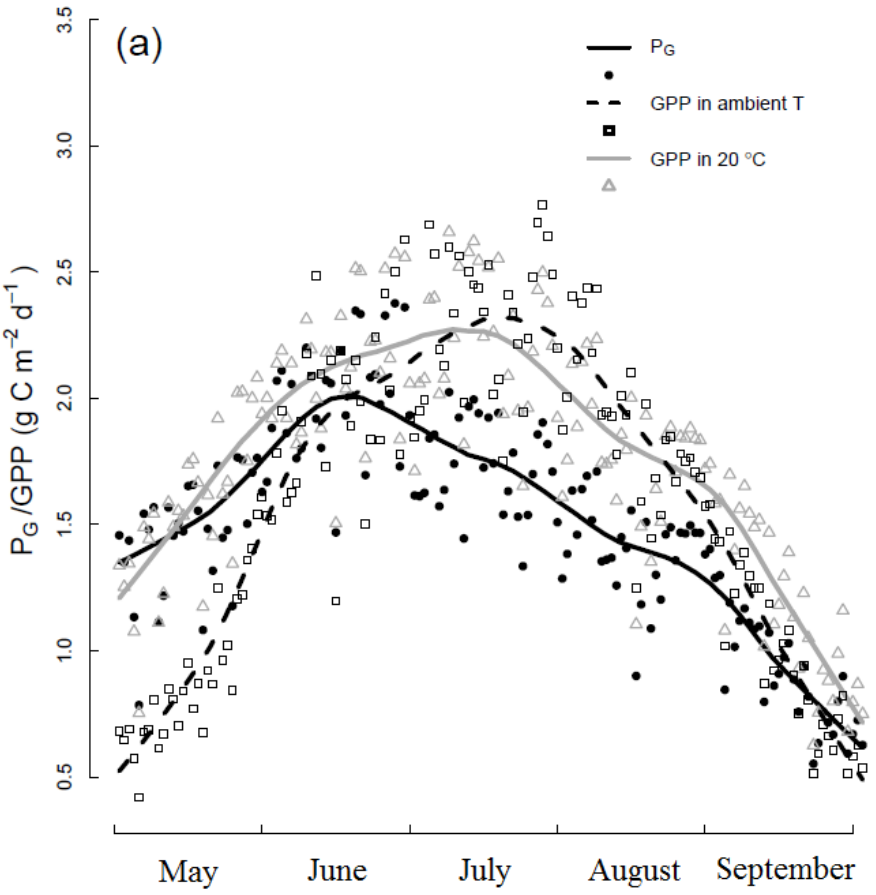

Figure 8. Comparison of the upscaled plant photosynthesis P_g, eddy-covariance GPP (at ambient T) and model of eddy-covariance GPP with fixed temperature (at 20˚C). Adopted from **Paper II**.

Over the growing season (May-September), the cumulative P_g summed up to 230 gC m^{-2}, while the EC GPP gave 243 gC m^{-2}. Those values can be considered to match, given the uncertainties involved in each of the methods. While it was impossible to derive a reliable uncertainty estimate for the upscaled plant photosynthesis for practical reasons (**Paper II**), a component of EC GPP uncertainty was examined. A major source of uncertainty lies in the partitioning of the measured NEE into R_e - GPP. This involves the use of R_e and GPP models, which have a total of four parameters (R_{ref}, Q_{10}, P_{max} and k, according to Eqs. 8 and 9). Via independent variation of the four parameters within their specific confidence intervals, 1000 estimates of cumulative EC GPP were obtained. The mean ± STD of the cumulative EC GPP was determined from the resulting distribution as 243 ± 11 gC m^{-2} (Fig. 9). Note that this is just a fraction of a total uncertainty (e.g. Aubinet et al., 2012), which, even in ideal sites, may reach 50 gC m^{-2} annually (Baldocchi et al., 2003).

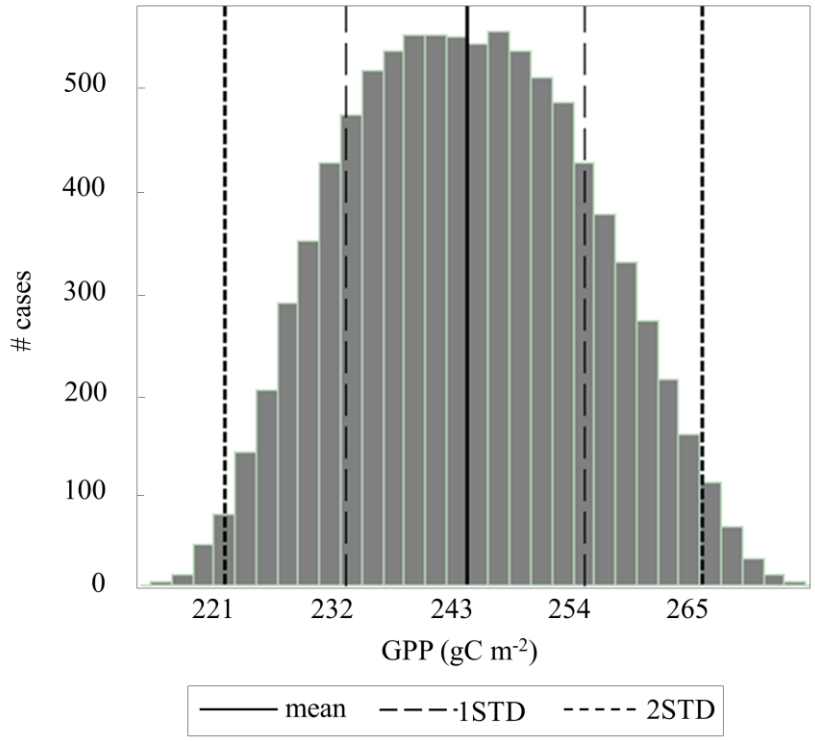

Figure 9. Distribution of cumulative SI2 GPP values calculated from a population of 1000 cumulative GPP estimates obtained by varying the R_e and GPP model parameters within the respective confidence intervals. The mean value of the distribution is 243 gC m^{-2} and the STD is 11 gC m^{-2}.

4.2 Ecosystem scale: ecosystem-atmosphere interactions in a boreal bog

Measurements of ecosystem-atmosphere exchange of energy and CO_2 were conducted in the Mukhrino bog in May-August 2015. That year was characterized by an early warm spring and, later, a cool and wet summer – a sequence quite untypical for the regional climate. Throughout the measurement period, cool temperatures and high wetness were retained thanks to several cold front passage events.

The CO_2 flux data were gapfilled following the method described in Section 3.3. Throughout the study period, the bog was a relatively strong sink of CO_2, with the four-month cumulative NEE reaching -202 gC m^{-2} (Fig. 10). This breaks down into R_e and GPP of 157 gC m^{-2} and 359 gC m^{-2}, respectively. Such an uptake magnitude is high for this type of ecosystem. However, this might have been partly due to the cool and moist conditions that favored *Sphagnum* moss growth. A similar effect was observed in **Paper II**, where early productivity of the ecosystem was ensured by mosses at the time when vascular plant growth was limited by low temperature. Generally, the seasonality of the GPP and R_e parameters in Mukhrino (Fig. 7 in **Paper III**) can be seen as an integral of the contributions by individual species, as found in **Paper II** and Korrensalo et al. (2016).

The cumulative exchange values observed in Mukhrino might seem high, but comparable observations do appear elsewhere. Very wide variation in annual net uptake was found in

Mer Bleue, with some years yielding cumulative NEE on a par with that found in Mukhrino (Roulet et al., 2007; E. Humphreys, personal communication). There, it was strongly controlled by interannual weather variations. Maximum summer photosynthesis P_{max} of Mer Bleue (10.7-12.4 μmol m^{-2} s^{-1}) is also equivalent to P_{max} of Mukhrino (11.5-12.5 μmol m^{-2} s^{-1} in June-July) (Humphreys et al., 2014). Generally lower net uptakes were reported at various boreal mires by Arneth et al. (2002), Friborg et al. (2003), Dolman et al. (2012) and Humphreys et al. (2014) (the Attawapiskat river and Kinoje lake sites). In Mukhrino, most of this uptake occurred in the months of June and July, when there was no moisture limitation and the total LAI was at its maximum (Fig. 11). A dry growing season that followed in 2016 showed substantially lower photosynthesis and higher respiration (unpublished data).

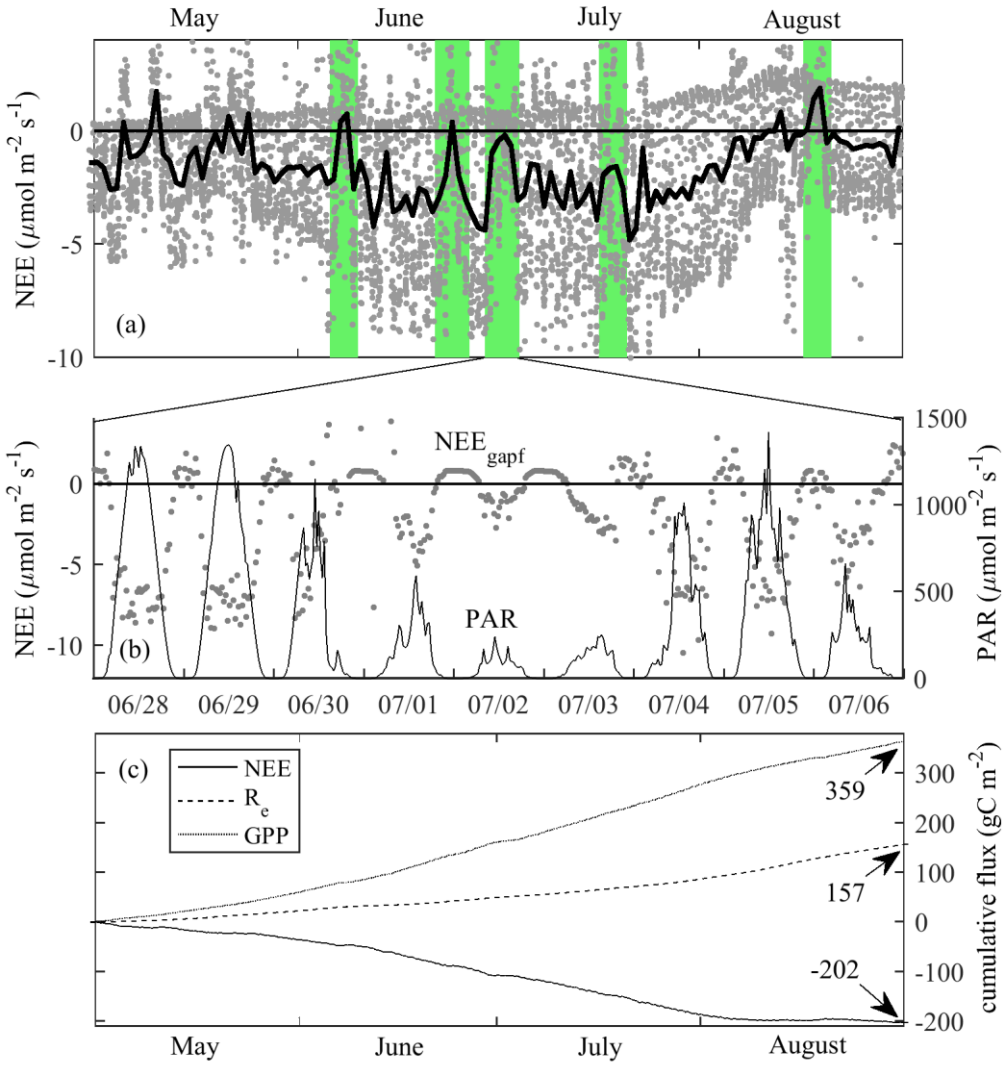

Figure 10. Gapfilled NEE (a) with the colour stripes showing the periods of cold front passage; (b) a closer look at the NEE and PAR evolution during one of the fronts; (c) cumulative NEE and its components. Adopted from **Paper III**.

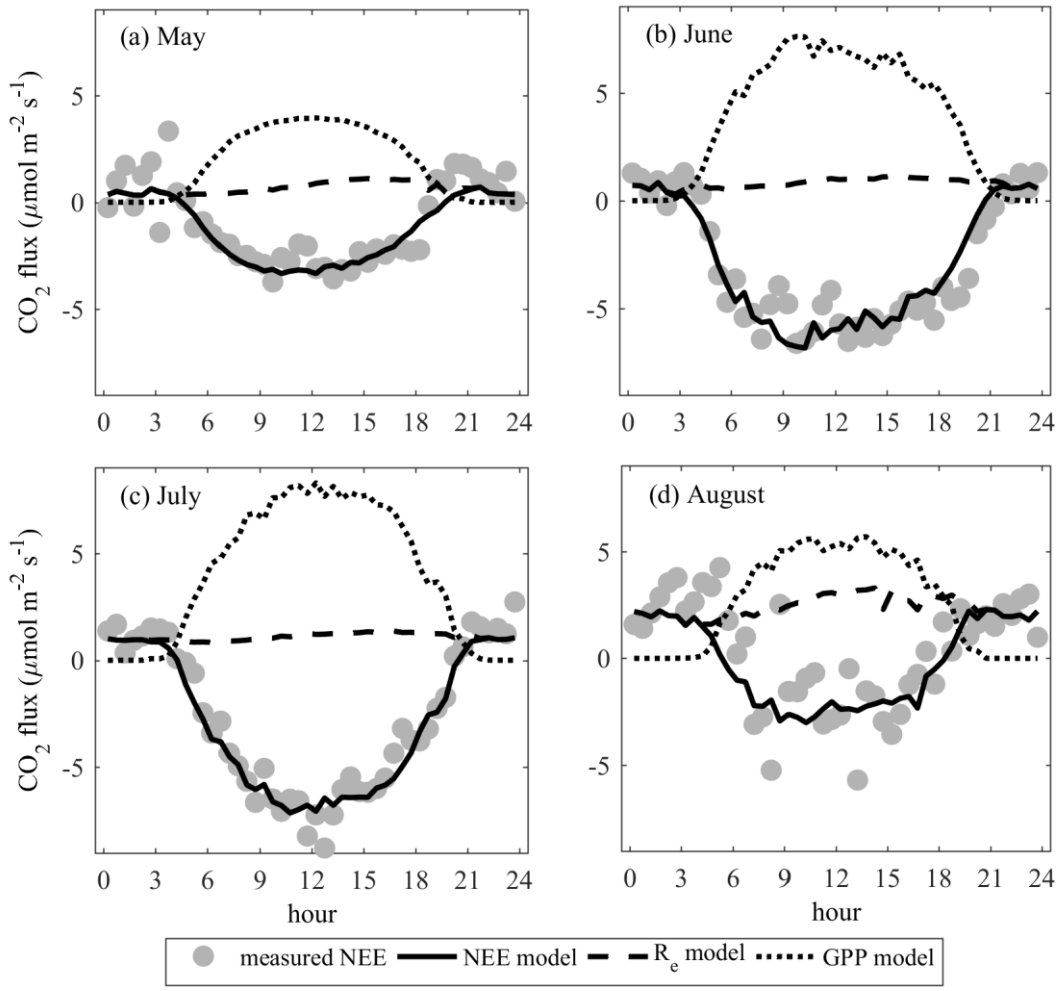

Figure 11. Diurnal courses of NEE, R_e and GPP averaged for the four study months. The grey circles show NEE values observed with eddy-covariance. See section 3.3 for details on NEE, R_e and GPP modeling approach.

4.3 Multisite scale: energy balance features of boreal mire types

The summertime (May-October) energy balances of eight Finnish and Swedish peatlands were explored in **Paper IV**; in addition, similar analyses were brought out for the West-Siberian peatland of Mukhrino in **Paper III**. Substantial differences in terms of energy balance components and environmental drivers between the studied ecosystems were found. Importantly, it proved possible to associate this diversity of the energy balances with the peatland ecosystem type. A major role in determining the energy balance of a site was attributable to the dominant vegetation and hydrology. Let us now review the results per ecosystem type:

a) The presence of tree canopy (of variable density) and relatively low water table in several peatlands (ALK, KAL, FAJ and MUK) leads to certain similarity with the energy balance of boreal forests growing on mineral soil. For example, KAL and ALK energy budgets resemble that of SMEAR-II forest (Launiainen, 2010). In treed peatlands, the tree

physiological regulation and relatively low water table together lead to constrained evapotranspiration, which is shown by low bulk surface conductance. The combination of these factors leads to a relatively high Bowen ratio, good coupling with the atmosphere, and low ratio of actual to potential ET (Fig. 12). Another effect of the tall tree canopies in KAL and ALK is a high aerodynamic conductance, as opposed to the rest of the sites which are more resistant aerodynamically (Fig. 12d). However, despite the densest tree cover of the natural mires, the Mukhrino energy balance resembled those of the other natural boreal peatlands studied in **Paper IV** or elsewhere. The energy balance closure was close to 100% and the Bowen ratio averaged to 28% over May-August. While much higher ß may be found at raised bogs (e.g. 1.35 in FAJ), ß in Mukhrino was closer to the estimates for the open fens SI1 and SI2 and bog SI2 (0.31-0.45, **Paper IV**). In terms of resistance to evapotranspiration, MUK lies between the open mires (SI1, SI2 and DEG) and the tree-covered raised bog FAJ. However, the MUK enegy balance in 2015 might have been altered compared with the multiannual average through an impact of unusually wet and cool weather, so that the multiannual averages of ß and r_s are probably higher.

b) The natural open mires (DEG, SI1 and SI2) lack tree cover, and as such have energy exchange mainly controlled by the amount of water at the moss surface. Here, vascular plants do not play a defining role, as a large fraction of energy exchange occurs at the moss, bare peat or water surfaces. Besides, given a typically waterlogged state, bulk surface conductance is never low. Self-regulation in the face of external forcing, inherent to natural mires (Loisel and Yu, 2013; Swindles et al., 2012), helps to sustain a seasonally stable energy exchange – manifested as low and nearly constant Bowen ratio. As a rule, these mires are poorly coupled with the atmosphere and have a high ET/PET_P. It should be noted that MUK, although assigned to the treed peatland group, bears similarity with the open mire group, so that it in many instances appears to fall between the two groups (Fig. 12). However, its exposure to a different West-Siberian climate (and unusually wet weather in 2015) limits the potential similarity with any Fennoscandian sites.

c) Peat croplands JOK and LIN represent the two alternative uses of peatland for crop cultivation, e.g. forage grass/barley and reed canary grass, respectively. Crop cultivation requires low water table, which is achieved through drainage. Peat harvesting is also common, as illustrated by LIN. In the absence of other vegetation, the seasonality and mean levels of energy balance parameters are completely dependent on crop phenology. In terms of mean parameter values, JOK and LIN fall between the natural open mires and tree-covered peatlands. However, the qualitative similarity notwithstanding, the two cropland sites proved to be very disparate in quantitative sense, as their ß, ET/PET_p and g_s differed considerably. This was probably due to the specific ecophysiology of the cultivated species. The agricultural peatlands may be seen as outliers: while both open and treed peatlands do occur naturally in the Boreal climate, dense and tall graminoid vegetation does not.

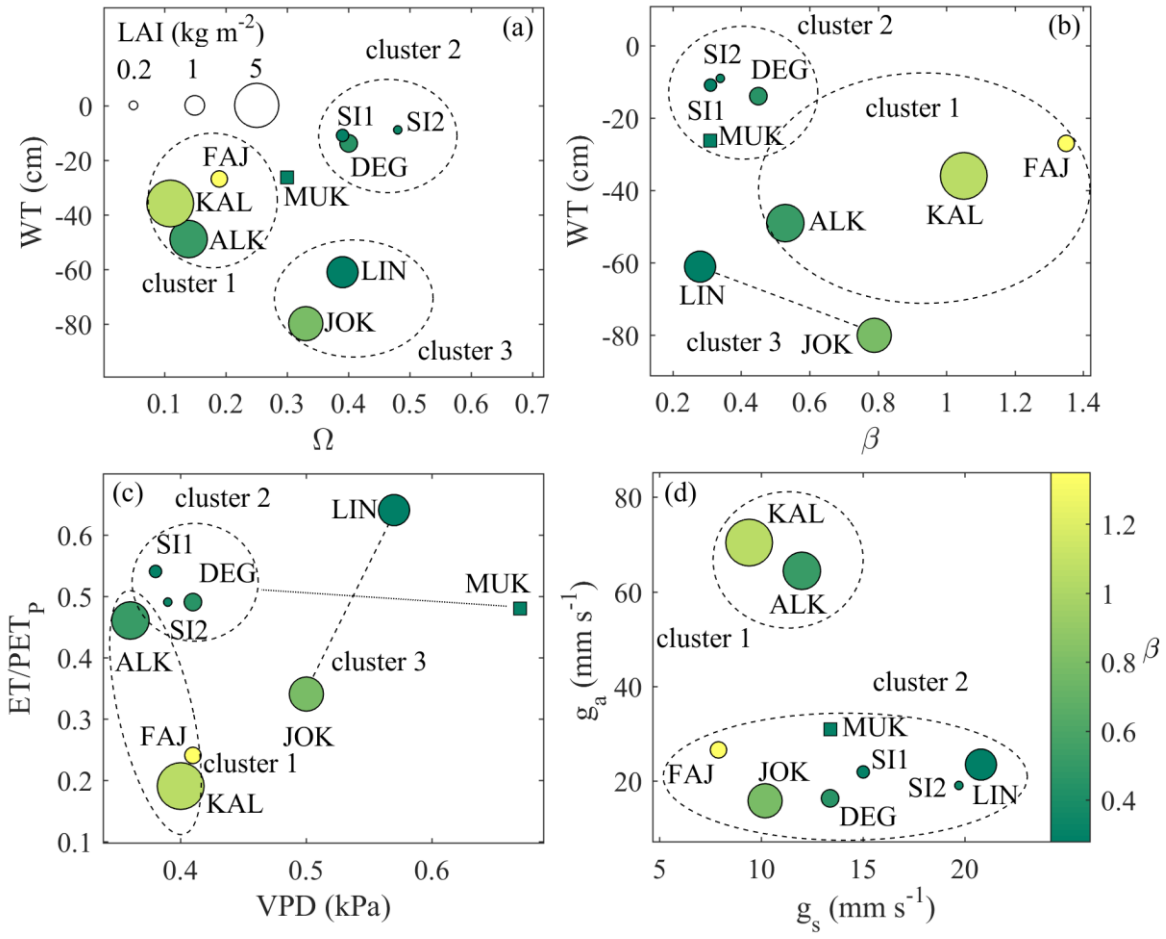

Figure 12. Visualization of mean energy balance parameters and important environmental drivers. Adapted from **Paper IV**, modified. The major environmental factors (WT, VPD, LAI) are presented as drivers of the ecosystem features such as decoupling factor (a), Bowen ratio (b) ET/PET_p (c), while (d) gives a relationship between the aerodynamic and bulk surface conductances. The clusters are defined visually based on numerical and/or ecological similarity between the sites. MUK is assigned the leaf area index of FAJ, as the sites are similar and the actual value in MUK has not been measured to date. Leaf area index is shown as marker size and Bowen ratio as color.

4.4 Global view: How representative are the current environmental measurements in Eurasia?

We began the analysis with an assessment of the geographical distribution of the measurement sites that target atmospheric sciences, ecology, biogeochemistry and, broadly, climate change in Eurasia. A detailed review of the North-Eurasian measurement facilities was made based on the survey. The sites considered in the overview amount to 466, of which 206 are in Russia, 75 in China and 185 in Europe, Greenland, Canary Islands and Kyrgyzstan (Fig. 2; the nine study locations listed in Table 1 are highlighted). The sites in Russia were additionally classified according to the level of their development, i.e. the complexity of the measurement setup and other infrastructure. In the

analysis of the station equipment, attention was paid to the presence of state-of-the-art equipment for ecosystem-atmosphere flux and aerosol measurement.

The poor spatial coverage in the Russian territory, compared with that in Western Europe, is striking. Moreover, the distribution is skewed towards Russia's more populated European part. Similarly, the Chinese network lacks density in some areas, and the western half of the country is about as sparsely covered as Siberia. However, Russia, China and Western Europe are to some extent complementary, as they dominate in different latitudes. The latitudinal distribution (Fig. 2 in **Paper V**) highlights this pattern.

The climate map of North Eurasia is very diverse, spanning the spectrum from hot deserts to the harsh Arctic. The climates generally change with latitude, but there is also a notable longitudinal variation due to the east-west gradient in continentality. Presenting the measurement sites on a climate map (Fig. 6 in **Paper V**) makes it obvious that the distribution is far from optimal, with some climates housing many stations and others none. Note that this is still a heavily simplified picture: first, the Köppen-Geiger climate zones have internal variability; second, a large number of ecosystem types can be found in each climate. We tried to formally approach this complexity by looking at the number of Russian stations in individual climate-ecosystem combinations (Table 2). It appears that many climates and ecosystems are not represented at all, whereas most measurements are made in the forests and urban areas located in major Boreal climates Dfc, Dfb and Dfd.

Table 2. Count of measurement sites representing the possible ecosystem/climate combinations in Fennoscandia and Russia. The ecosystem/climate combinations covered with at least one station are color-coded with green.

Köppen-Geiger climate type	Area fraction (%)	K-G index	Ecosystem types							
			freshwater	wetland	forest	steppe	high-elev.	tundra	marine	urban
mild desert	1.5	Bwk	0	-	-	-	-	-	-	0
mild steppe	5.9	Bsk	0	-	-	1	1	-	0	0
humid subtropical	<<1	Cfa	1	0	0	-	2	-	1	0
humid continental	<<1	Dsb	0	0	0	-	0	-	0	0
boreal, cold summer	0.5	Dsc	0	0	0	-	0	-	0	0
boreal, very cold winter	0.1	Dsd	0	0	0	-	0	-	-	0
humid continental, hot summer	0.7	Dwa	0	0	0	-	0	-	0	0
humid continental, warm summer	0.2	Dwb	1	0	2	-	2	-	0	2
boreal, cold summer	7.5	Dwc	2	0	14	1	1	1	0	2
boreal, very cold winter	1.6	Dwd	0	0	0	-	0	-	0	0
humid continental, hot summer	2.4	Dfa	0	0	0	-	1	-	-	1
humid continental, warm summer	19.5	Dfb	16	3	27	4	0	-	1	15
boreal, cold summer	44.3	Dfc	6	3	42	-	2	13	0	12
boreal, very cold winter	6.9	Dfd	0	2	4	-	0	0	-	1
polar/tundra	8.6	ET	0	0	-	-	0	25	1	0
polar/frost/ice	0.3	EF	0	-	-	-	0	-	1	-

We may then narrow down the view to specifically peatland measurements. Across Russia, I am aware of 8 peatland monitoring stations in the climates Dfc, Dfb and Dfd, of which only about 5 have eddy-covariance measurements (or have had in the past). However, Finland and Sweden contribute a further 11 stations to Dfc and Dfb, increasing the total count for the Eurasian boreal region to 19. While wetlands or, specifically, peatlands, may occur across a range of climatic zones (Vieder and Vitt 2006, Table 2), we may focus on the dominating climates Dfc, Dfb and Dfd that cover 71% of the North Eurasian territory (45˚-90˚ N, 15˚-180˚ E).

To add an ecological dimension, one could consider the fundamental peatland types as in Section 3.1. Table 3 offers an even more zoomed-in look at peatland measurements in Siberia. In this analysis, the stations equipped with EC are grouped by ecosystem types and climates, with Dfc split into the south, middle and north portions. It appears that half of the ecosystem/climate combinations are covered with at least one station with an EC setup. The problematic areas are, unsurprisingly, north taiga and the continental boreal climate Dfd, while the least measured peatland types are afforested and agricultural. Not a single EC station is currently representing the Dfc peatlands. Note also that the nine sites featured in this thesis actually cover a large fraction of the climatic-ecological continuum.

Table 3. Peatland sites equipped with eddy-covariance in northern Eurasia classified by ecosystem type and climate. The nine sites appearing in the papers of this thesis are highlighted. Note that EC measurements were also made for a short period at the Plotnikovo station in a hemi-boreal bog. See Table 1 for site codes.

	Dfb, hemi-boreal	**Dfc, boreal**			**Dfd, continental boreal**
		south taiga	**middle taiga**	**north taiga**	
Bog	**FAJ**	**SI2**, Tervalamminsuo (FI)	**MUK**, ZOTTO (RU)	-	-
Fen	Zapovednik (RU)	**SI1**	**DEG** Ust-Pojeg (RU)	Kaamanen (FI), Lompolojänkkä, (FI) Halssiaapa (FI)	-
Afforested peatland	Skogaryd (SWE)	**ALK, KAL** Lettosuo (FI)	-	-	-
Agricultural peatland	-	**LIN, JOK**	-	-	-

5 Conclusions and outlook

The present thesis investigated the peatland diversity on different spatial scales, and the emerging patterns proved to be complex and scale-dependent. The declared Aims,

addressing different components of this variability, have been achieved. Let us begin with plant-microsite scale properties of peatlands, which proved to be well related to the equivalent estimates made on an ecosystem scale. In two novel approaches, aerodynamic roughness length was compared with ecosystem level leaf area index (**Paper I**), whereas upscaled individual plant photosynthesis was compared with gross primary productivity measured by eddy-covariance (**Paper II**). The temporal course of a purely physical parameter, aerodynamic roughness length, followed the seasonality of leaf area index, whereas the eddy-covariance GPP was reasonably close to the upscaled photosynthesis of individual species. Such a close relationship between the direct/manual measurements and "indirect" aerodynamic measurements on an EC tower lends further credibility to upscaling methodologies and opens up new possibilities for a broad range of models incorporating peatland-atmosphere exchange.

Stepping up on the spatial scale, energy balances of eight boreal peatlands were investigated in **Paper IV**, including one site from **Paper III**. The expectation of clear separation between the different peatland types in terms of energy balance features was fully confirmed. The natural fen-bog gradient and the anthropogenic land-use features proved to form unique energy balances in each respective peatland class. In accord with this result, we observed site-dependent effects of the environmental and biotic factors on energy balance variations. The general pattern is that of tight clustering of the natural mires in regard to most important parameters with $\beta \approx 0.35$, $\Omega \approx 0.4$, $ET/PET_P \approx 0.5$ and $g_s \approx 17$ mm s^{-1}. In turn, the peatlands having dense vegetation and/or low water table diverge from that "natural" cluster in different directions that can be predicted based on site type. Treed peatlands generally move towards a higher β, lower Ω (due to higher g_a) and lower ET/PET_P. In contrast, agricultural peatlands may attain divergent characteristics depending on crop type and management approach. This evidence may help resolve the peatland mosaic at higher resolution, and eventually contribute to model improvement.

Representativeness of the ground-based monitoring station network was assessed on a continental scale in **Paper V**. This work was part of the greater PEEX initiative to analyze, harmonize and improve the environmental measurement network across Eurasia. The survey made in this thesis highlighted the deficiencies of the current monitoring station network. Siberia turned out to be a particularly heterogeneous region, some parts of it covered well but others mostly devoid of monitoring. In order to elucidate another dimension of the problem, we inquired into how well the individual ecosystem-climate pairs are covered with measurement; particular attention was paid to the state-of-the-art instrumentation (e.g. eddy covariance), which understandably proved to be lacking in many regions. We are positive that the presented method of site network assessment may be improved and applied more widely to plan specific upgrades in the PEEX measurement network.

One of the "white spots" in the measurement coverage was eliminated by the creation of a new West-Siberian station, Mukhrino, where eddy-covariance measurements were launched in the spring of 2015 (**Paper III**). Carbon dioxide, water vapor and energy flux exchanges were consistent with the other boreal peatlands. However, the May-August net

CO_2 uptake was among the highest estimates ever obtained from similar ecosystems: higher than any other Eurasian boreal bog, and similar to only the Canadian Mer Bleu. At the same time, the surface energy balance resembled the estimates from open natural mires. However, the results of 2015 hardly represent a typical situation, because of the unusual weather – an early spring followed by a wet summer. The contrastingly dry summer of 2016 (unpublished data) gave an indication of a much lower net CO_2 uptake, meaning that only a multiannual dataset may provide a full picture.

Besides, the following remarks can be made:

- First, from **Papers I** and **II** it follows that the combination of peatland plant- of microsite-scale measurements and aerodynamic techniques is a promising field for further research. Direct benefits can be expected - for instance, the possibility to gap-fill the timeseries of EC GPP using an upscaled plant model. Here, one has to ensure that the small-scale measurements are representative of the EC footprint; this should be taken into account in the follow-up studies of the Mukhrino peatland (**Paper III**). Note that the results of **Papers I** and **II** are also applicable to understorey vegetation in forested ecosystems – it often represents a mosaic of vegetation communities not unlike that in open peatlands, which is relevant for subcanopy EC studies.
- Second, leaf area index, being a parameter of universal importance (appears in **Papers I-IV**) should be given more attention as a link between energy and carbon balances, turbulence and plant ecophysiology. While it is hard to imagine that careful LAI measurements (as in **Papers I, II**) will be undertaken at all eddy-covariance sites, routine application of a z_0-based approach seems possible.
- Third, ecosystem management status (**Paper IV**) should be taken into account when planning the extensions to North-Eurasian measurement network (**Paper V**). While the proportion of disturbed ecosystems is increasing, they are rarely monitored in eastern Eurasia. In this connection, it is worth remembering that one of the ultimate aims of this research is the reconstruction of large-scale budgets. Being expensive, eddy-covariance sites will remain relatively far apart, so that a well-planned measurement network both giving a broad view of a "background" but also targeting the hotspots and disturbances will be needed.

It is now widely recognized that complete understanding of the continental-scale ecosystem-atmosphere exchanges is impossible without detailed knowledge of their constituents on each scale. Of all ecosystems, peatlands are what truly embodies the concept of variability. Investigations compiled here were, to a great degree, motivated by the interest to tackle that elusive property. The results obtained throughout this thesis equivocally suggest that many aspects of peatland diversity remain to be explored in greater detail; they delineate directions for further attempts to understand the internal variability and, ultimately, the role of peatlands in the Earth system.

Review of publications and author's contribution

Paper I proposes the new method for determining the sedge leaf area index in a natural boreal mire. The method is based on the use of LAI regression against the aerodynamic roughness length for momentum and has not been tested before. I formulated the idea, analyzed the data and wrote the manuscript.

Paper II investigates the boreal peatland photosynthesis on a microsite scale and tests the fidelity of the upscaled microsite GPP values by comparing them with the eddy-covariance GPP. A high degree of similarity is observed between those independent estimates. I was responsible for the processing and presentation of the eddy-covariance data and related analyses, and made contributions to the text.

Paper III presents the first data on meteorology, CO_2 and energy exchange from the new station in a remote part of West-Siberian middle taiga, Mukhrino. Four months of data are analyzed, the budgets and their components, and the effects of the environmental drivers are discussed. I participated in the field installations, performed all raw data collection and quality control, post-processing and all analyses, and wrote parts of text throughout the paper.

Paper IV. The paper summarizes the energy balance features of eight boreal peatlands, focusing on the importance of the ecosystem types. The energy balance components, effects of the environmental drivers and other relevant features are discussed in the framework of peatland diversity: separately for natural fens and bogs, agricultural and afforested peatlands. I compiled and analyzed the data, and wrote the paper.

Paper V offers a review of the North-Eurasian ecosystem monitoring site network. A number of problems, including the geographical distribution, climate and ecosystems representativeness, and comprehensiveness of the instrumentation, are treated. I collected the data, formulated the analysis methods, and wrote the paper.

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